0.5 setgray0 0.5 setgray1

# Transverse Spin at HERMES

## 2005 2nd Joint Meeting of DNP of APS and JSPS, Maui

**Wolf-Dieter Nowak**

DESY, D-15738 Zeuthen

`Wolf-Dieter.Nowak@desy.de`

For the hermes Collaboration

# Table of Contents

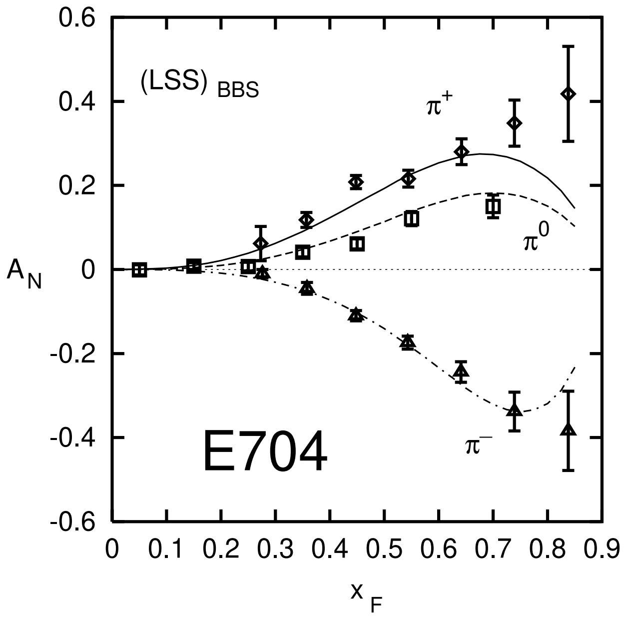
- Azimuthal asymmetries, transversity distribution function
- The Sivers distribution and Collins fragmentation functions
- The extraction method and its Monte Carlo validation
- The HERMES spectrometer and transversely polarized target
- Results on moments of Sivers and Collins asymmetries from SIDIS (semi-inclusive deeply inelastic scattering)
- Result on separation of subleading 1/Q contribution in SIDIS
- Result on asymmetry in 2-Pion (interference) final state
- Summary and outlook

# Azimuthal Asymmetries: A Clue to Spin Physics?

Significant single-spin asymmetries observed in

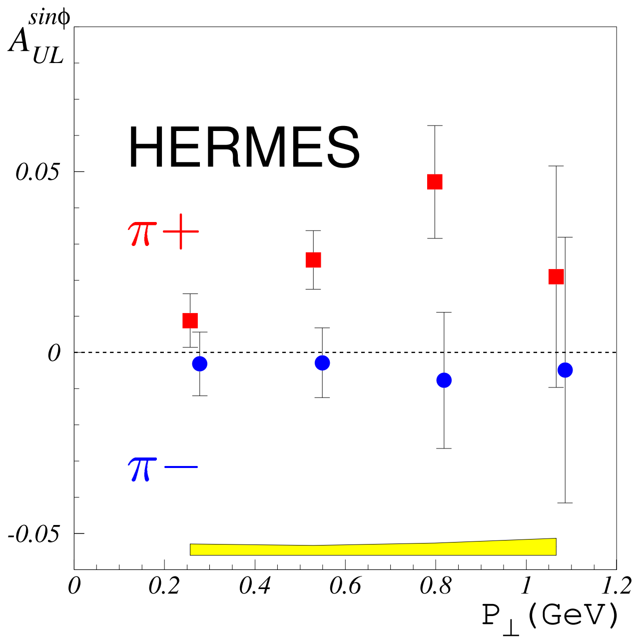
- $p^\uparrow p$ or $\bar{p}^\uparrow p \longrightarrow \pi^\pm + X$ (E704/FNAL, 1995): $\mathbf{A_N}$
- $e p^\rightarrow \longrightarrow e' \pi^\pm + X$ (HERMES, 2000): $\mathbf{A_{UL}}$

  unpol. beam (U), longitudinally pol. target (L)




Theoretical explanations:

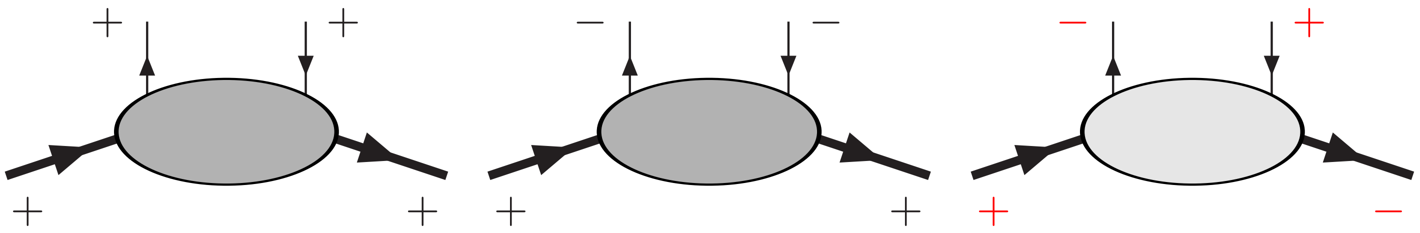
- **'Collins' effect:** struck quark polarization correlates with transverse momentum ($k_T$) in fragmentation
- **'Sivers' effect:** struck quark transverse momentum ($p_T$), correlated with nucleon polarization through distribution function, will be inherited by produced hadron



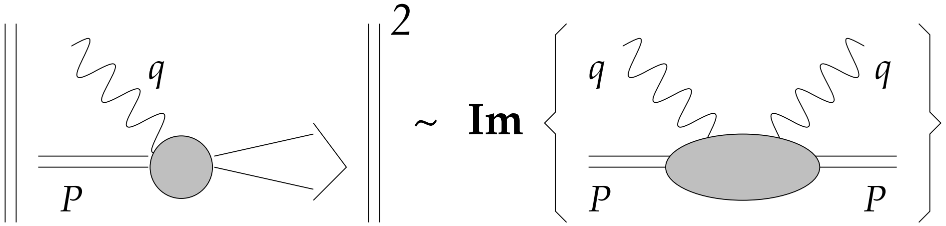

⇒ **effects indistinguishable in HERMES $\mathbf{A_{UL}}$ & E704**

⇒ **HERMES transversely polarized target: hope to untangle Collins from Sivers effect by measuring the transverse single-spin asymmetry $\mathbf{A_{UT}}$**

# Probabilistic Interpretation of Transversity




Optical theorem:




$$
\begin{aligned}
q(x) &= \quad q^{\rightrightarrows}(x) + q^{\rightleftarrows}(x) \quad \sim Im(\mathcal{A}_{++,++} + \mathcal{A}_{+-,+-}) \\
\Delta q(x) &= \quad q^{\rightrightarrows}(x) - q^{\rightleftarrows}(x) \quad \sim Im(\mathcal{A}_{++,++} - \mathcal{A}_{+-,+-}) \\
\delta q(x) & \quad alias \quad h_1(x) \quad \sim Im\, \mathcal{A}_{+-,-+}
\end{aligned}
$$

Positivity limit & Soffer bound:

$|\delta q(x)| < q(x)$

$|\delta q(x)| < \frac{1}{2}\,(q(x) + \Delta q(x))$

**In the helicity basis:**

$\Leftarrow$ 3 independent helicity amplitudes of quark in nucleon

- transversity $\delta q(x)$ can be identified with helicity flip amplitude
- BUT: NON-diagonal

$\Rightarrow$ no probabilistic interpretation!

**In transverse Spin basis:**

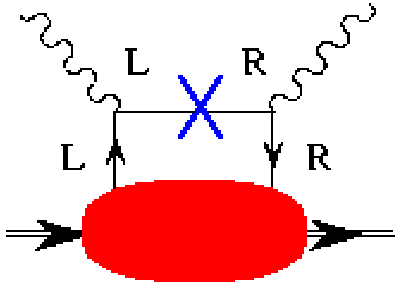
- amplitude is diagonal:

$$\delta q(x) \sim Im\,(\mathcal{A}_{\uparrow\Uparrow,\uparrow\Uparrow} - \mathcal{A}_{\uparrow\Downarrow,\uparrow\Downarrow})$$

$\Rightarrow$ probabilistic interpretation:

$$\delta q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$$

# How to Measure Transversity?




- Hard interactions conserve chirality
- $\Leftarrow$ In DIS: chirality-flip diagram suppressed by quark mass
- The transversity distribution function is chiral-odd
  $\Rightarrow$ not accessible in DIS!

**Semi-inclusive DIS**: $\boxed{\sigma^{\mathrm{eH}\to\mathrm{ehX}} \propto \sum_{\mathrm{q}} \mathcal{D}^{\mathrm{H}\to\mathrm{q}} \otimes \sigma^{\mathrm{eq}\to\mathrm{eq}} \otimes \mathcal{F}^{\mathrm{q}\to\mathrm{h}}}$

where $\mathcal{D}$ denotes a distribution function and $\mathcal{F}$ a fragmentation function
(Factorization not yet proven for transverse-momentum-dependent subleading 1/Q terms)

Need another chiral-odd object: **Collins fragmentation function $\mathbf{H_1^\perp}$**

- also 'T-odd' (=odd under naive time reversal)
- represents interference of 2 amplitudes with different imaginary parts

  $\Rightarrow$ $\mathbf{H_1^\perp}$ can generate a single-spin asymmetry

NOTE: SIDIS alone can not independently determine $\delta q$ and $\mathbf{H_1^\perp}$ (only shapes!)

- $\mathrm{e^+e^-}$ can yield Collins function: BELLE (ongoing)
- Drell-Yan can yield transversity: upgraded RHIC, PAX ? (only large $\mathrm{x}$, 2012 ?)

# SIDIS: Two contrasting T-odd Phenomena

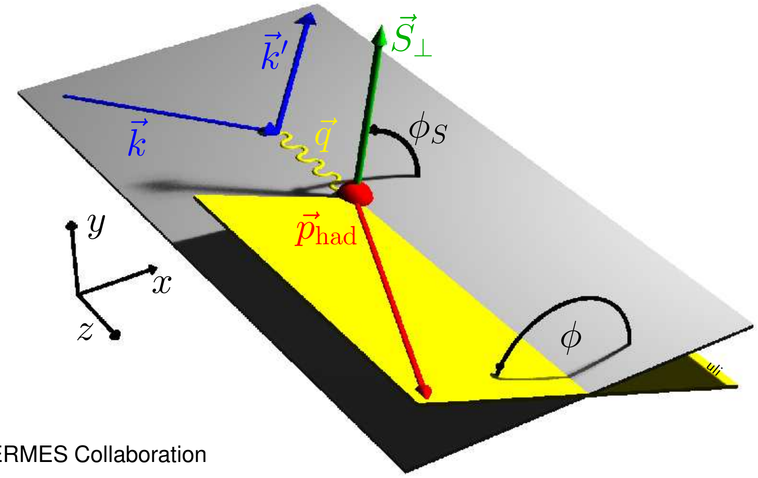
A single-spin asymmetry can arise from some (naive) T-odd mechanism

**With transverse target polarization two mechanisms become distinguishable:**

**Transversity + T-odd Collins FF**

- **Transversity:** polarizations of quark and nucleon correlated
- Photoabsorption flips quark polarization component in lepton scattering plane
- Quark polarization correlates with fragmentation $k_T \to \mathbf{P}_{h\perp}$ i.e. hadron production plane

$\Rightarrow$ Single Target Spin Asymmetry $\propto \sin(\phi + \phi_S)$




**T-odd Sivers distrib. function $f_{1T}^{\perp}$**

- $p_T$ of UNpolarized struck quark correlated with target polariz.
- $p_T$ survives fragmentation, inherited by hadron $\mathbf{P}_{h\perp}$

$\Rightarrow$ Orientation of lepton scattering plane is irrelevant

$\Rightarrow$ Single Target Spin Asymmetry $\propto \sin(\phi - \phi_S)$

# SIDIS Cross Section (to subleading order in 1/Q)

$\sigma_{XY}$

**Beam** **Target**
**Polarization**

$$d\sigma = d\sigma^{(0)}_{UU} + \cos 2\phi \, d\sigma^{(1)}_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^{(2)}_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^{(3)}_{LU}$$

$$+\mathbf{S_L}\left\{\sin 2\phi \, d\sigma^{(4)}_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^{(5)}_{UL} + \lambda_e \left[d\sigma^{(6)}_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^{(7)}_{LL}\right]\right\}$$

$$+\mathbf{S_T}\left\{\sin(\phi-\phi_S)\, d\sigma^{(9)}_{UT} + \sin(\phi+\phi_S)\, d\sigma^{(9)}_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{(10)}_{UT}\right.$$

$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{(11)}_{UT} + \sin\phi_S \, d\sigma^{(12)}_{UT}\right)$$

$$\left.+\lambda_e\left[\cos(\phi-\phi_S)\, d\sigma^{(13)})_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{(14)}_{LT} + \cos(2\phi-\phi_S)\, d\sigma^{(15)}_{LT}\right)\right]\right\}$$

**For transv.-mom.-INdep. terms: sub-leading 1/Q $=$ 'subleading twist'**

Mulders, Tangerman, Nucl. Phys. B 461 (1996) 197;

Boer and Mulders, Phys. Rev. D 57 (1998) 5780;

Bacchetta et al., Phys. Lett. B 595 (2004) 309

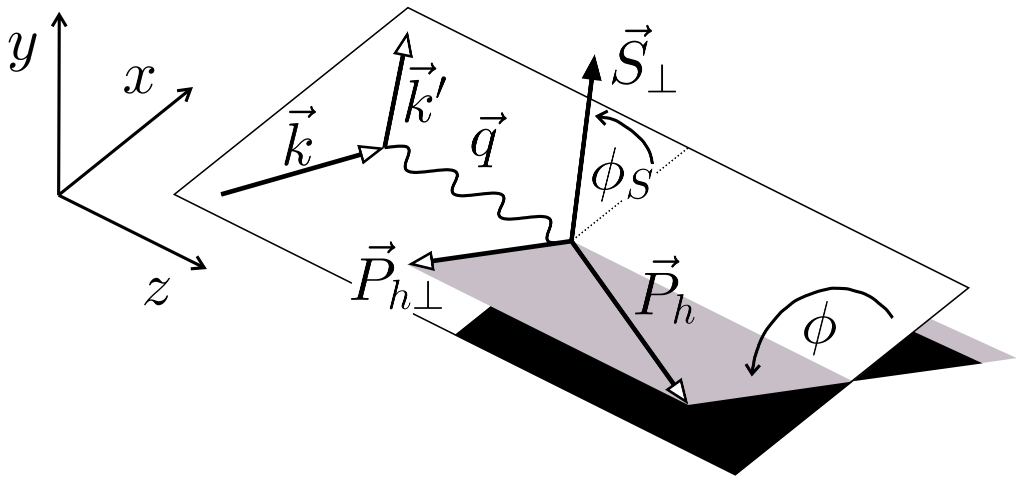
**THIS TALK:**

$\sin(\phi-\phi_S)\, d\sigma^{(8)}_{UT}$ ... Sivers term

$\sin(\phi+\phi_S)\, d\sigma^{(9)}_{UT}$ ... Collins term

$\sin\phi \, d\sigma^{(5)}_{UL}$ ... Long. target pol.

# Moments of lepton vs. photon axis




**Experiment**: Target Polarization aligned w.r.t. axis of beam lepton ($\ell$)

**Theory**: Azimuthal asymmetries taken around axis of virtual photon ($\gamma^*$)

$\Rightarrow$ **Mixing between $\ell$ and $\gamma^*$ moments** [Diehl, Sapeta, Eur. Phys. J. C41 (2005)]:

$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\ell} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\ell} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\ell} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\gamma^*} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\gamma^*} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\gamma^*} \end{pmatrix}$$

- No mixing between Sivers and Collins moments !
- $\cos\theta_{\gamma^*} \simeq 1$ , $\sin\theta_{\gamma^*}$ up to 0.15 at HERMES energies

$\Rightarrow$ tiny difference between $\ell$ and $\gamma^*$ moments: $0.075 \cdot \mathcal{O}(0.05) \leq 0.0035$ !

# Extraction of Sivers & Collins Azimuthal Moments

**Study azimuthal distributions of hadrons in:** $\mathbf{e^{\pm}\, p^{\uparrow} \longrightarrow e^{\pm}\, \pi^{\pm} \; + X}$

unpol. beam (U), transv. pol. target (T)

HERMES analysis uses Trento convention Phys. Rev. D70 (2004) 117504

First HERMES publication: Phys. Rev. Lett. 94 (2005) 012002

$$A^{\ell}_{UT}(\phi,\phi_S) = \frac{1}{\langle S_T \rangle} \frac{N_\pi^{\Uparrow}(\phi,\phi_S) - N_\pi^{\Downarrow}(\phi,\phi_S)}{N_\pi^{\Uparrow}(\phi,\phi_S) + N_\pi^{\Downarrow}(\phi,\phi_S)}$$

$$\sim \sin(\phi-\phi_S) \sum_q e_q^2\, \mathcal{I}\left[ w_{Siv}(p_T, P_{h_\perp}) f_{1T}^{\perp,q}(x,p_T^2)\; D_1^q(z,k_T^2) \right]$$

$$+ \sin(\phi+\phi_S) \sum_q e_q^2\, \mathcal{I}\left[ w_{Coll}(k_T, P_{h_\perp}) h_{1T}^q(x,p_T^2)\; H_1^{\perp,q}(z,k_T^2) \right] \quad + \quad \ldots$$

$\mathcal{I}[\ldots]$ : convolution integral over initial ($p_T$) and final ($k_T$) quark transverse momenta

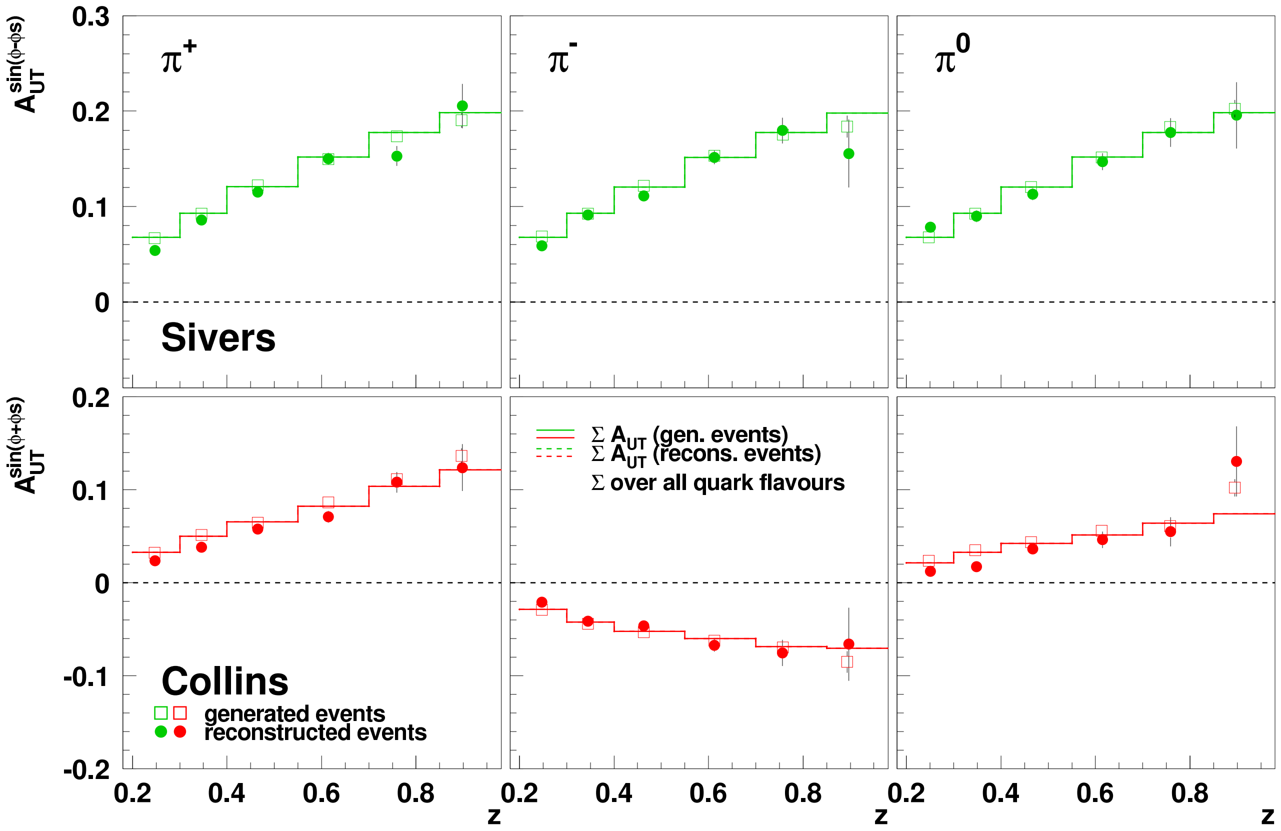
$\Rightarrow$ can NOT DIRECTLY extract transverse-momentum-dependent functions !

$\Rightarrow$ **Determine (simultaneously)** Sivers and Collins convolution integrals by a fit:

$$\boxed{A^{\ell}_{UT}(\phi,\phi_S) = 2\left\langle \sin(\phi-\phi_S) \right\rangle^{\ell}_{UT} \sin(\phi-\phi_s) + 2\left\langle \sin(\phi+\phi_S) \right\rangle^{\ell}_{UT} \sin(\phi+\phi_s)}$$

# Monte Carlo Validation of Extraction Method

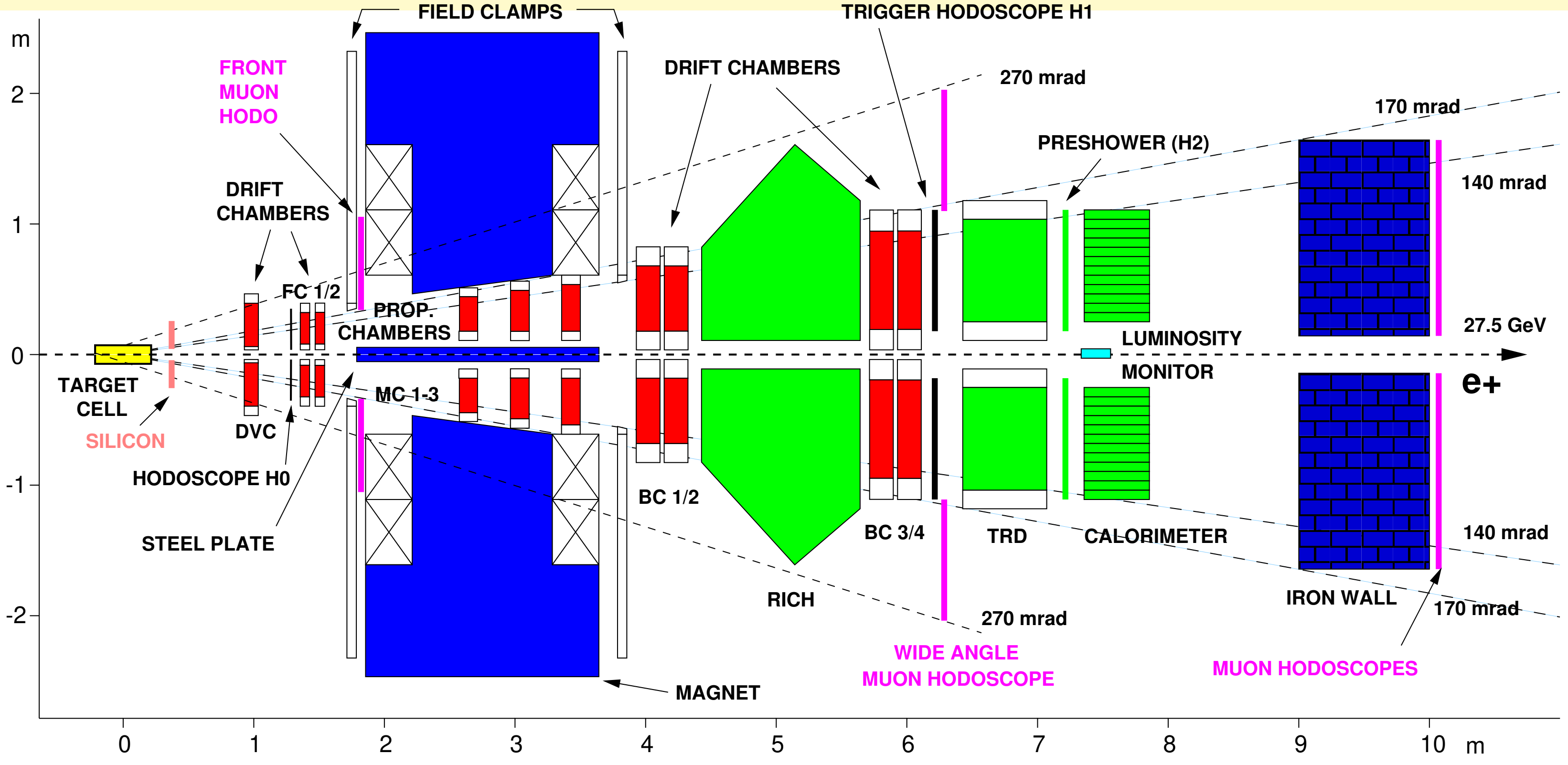
- generate Collins and Sivers asymmetries (Gaussian Ansatz in $\mathbf{p_T^2}$)
- analyze MC data like experimental data and extract asymmetries:




$\Rightarrow$ Collins-Sivers cross contamination negligible

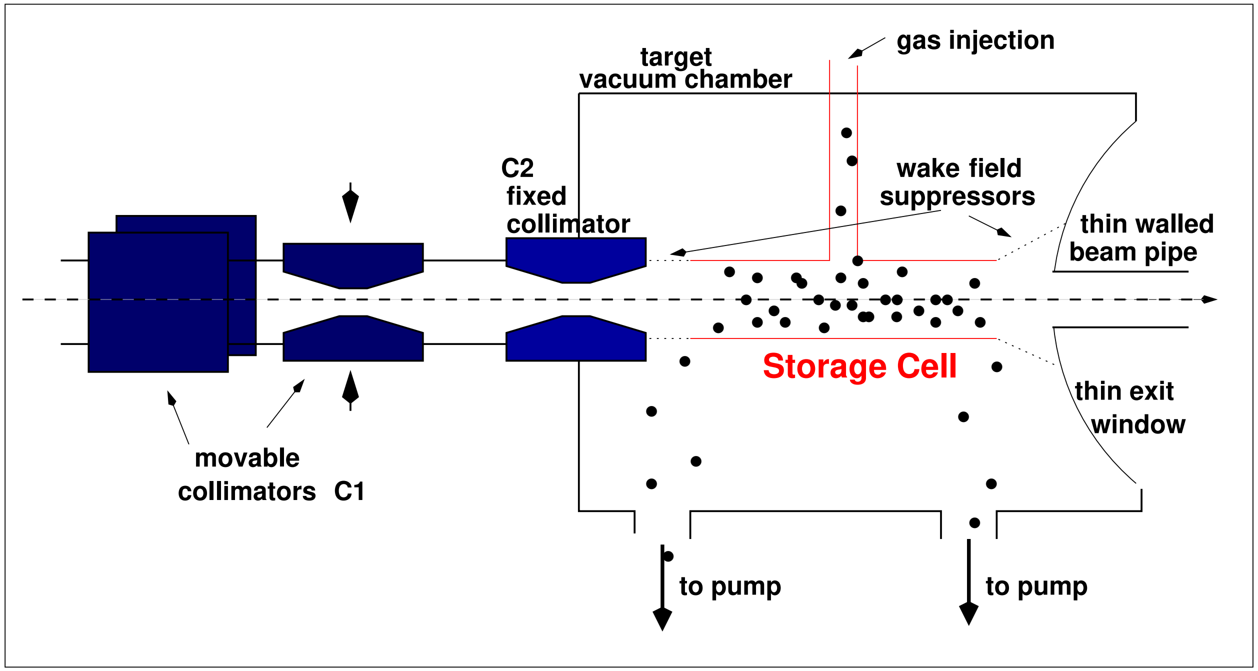
$\Rightarrow$ insensitive to transverse target tracking corrections

# The HERMES Spectrometer



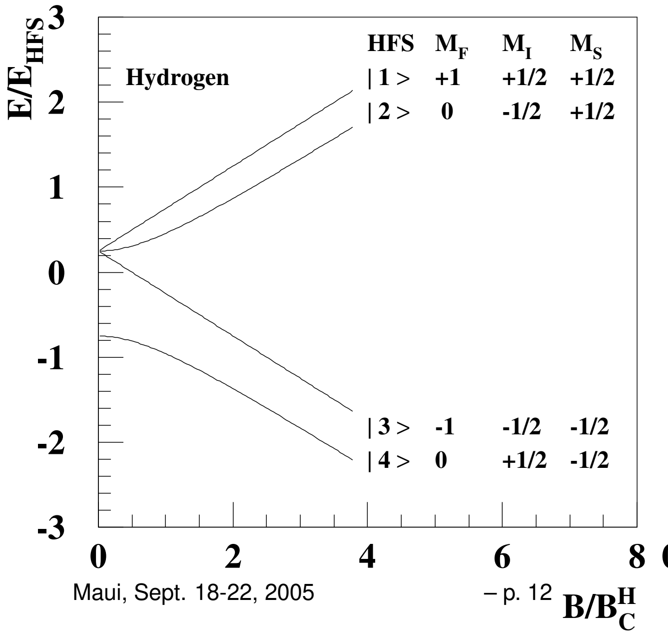

- Pure gas target: polarized H, D; unpolarized H, D, N, Ne, Kr, Xe
- Forward spectrometer: 40 mrad $\leq \Theta \leq$ 220 mrad
- Tracking: $\mathcal{O}$(50) tracking planes per half spectrometer: $\delta p/p \sim 2\%, \delta\Theta \leq 1$ mrad
- PID for $e^{\pm}$: TRD, Preshower, Calorimeter
- PID for $\pi^{\pm}, K^{\pm}, p$: Dual-radiator Ring-imaging Cherenkov ($2 < p < 15$ GeV)

# HERMES Internal Gas Target




Polarized hydrogen hyper-fine splittings

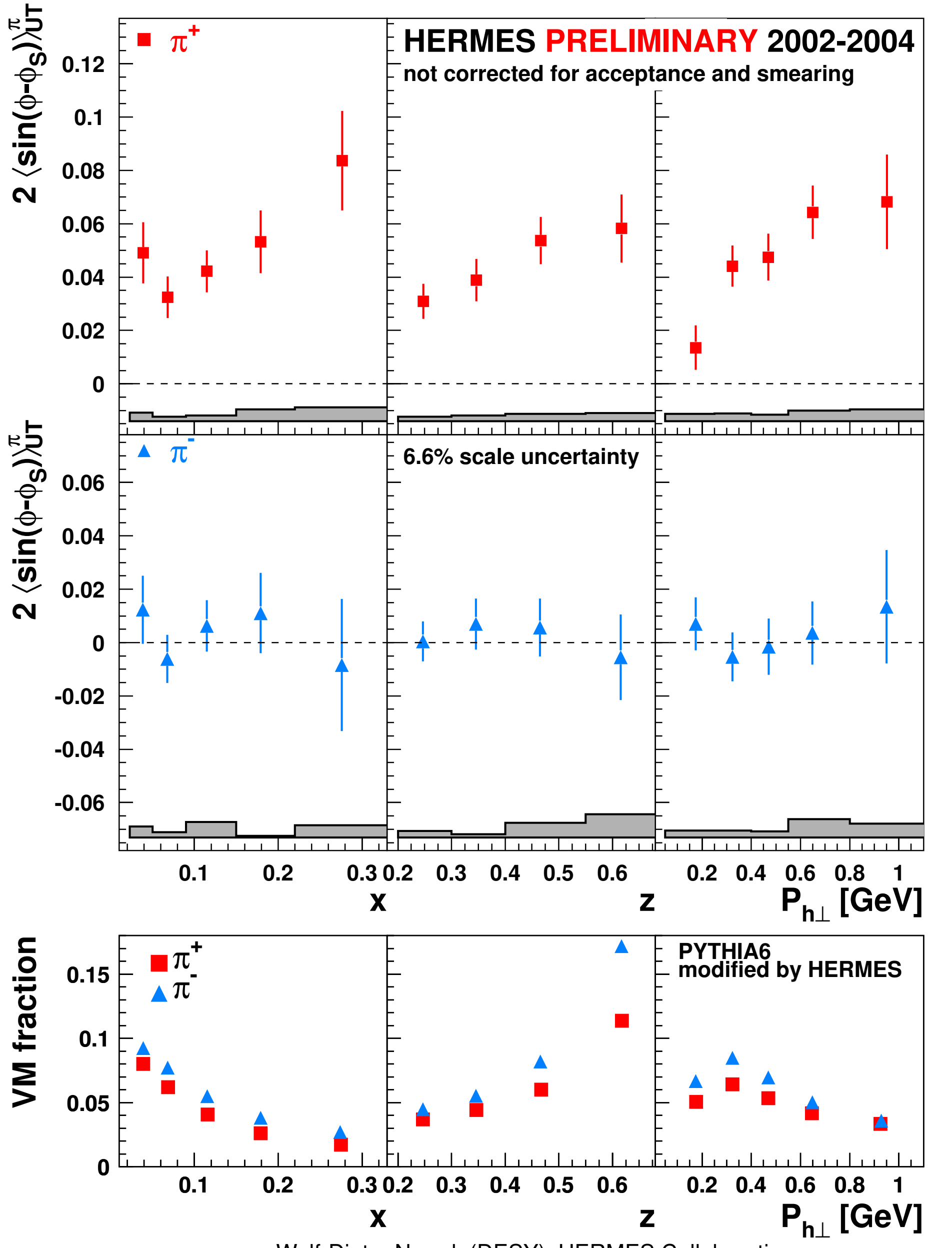
⇓




- Pure gas target ⇒ no dilution
- 60 s cycling time ⇒ low systematics
- Polarized gases: H,D (Storage cell fed by Atomic Beam Source)
- Unpolarized: H, D, He, N, Ne, Kr

# Results on Sivers Moments from 2002-2004 data

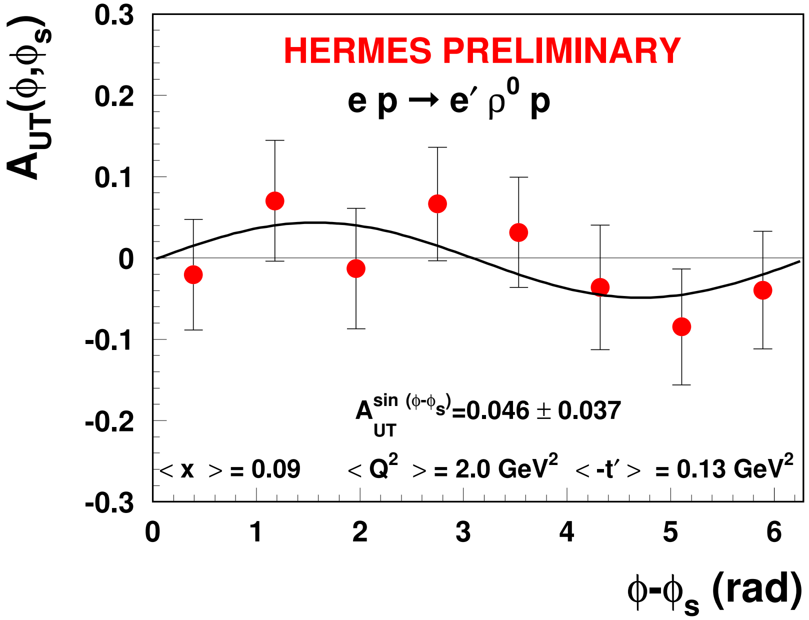
$$2\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{\ell} \approx 2\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{\gamma^*} \propto -\sum_q e_q^2\, \mathcal{I}\left[w_{Siv}\, f_{1T}^{\perp,q}(x,p_T^2)\, D_1^q(z)\right]$$




- $\pi^+$: positive; $\pi^-$: consistent with zero

$\Rightarrow$ first indication for non-zero Sivers fct.: $f_{1T}^{\perp,u}$ negative (as $\pi^+$ dominant)

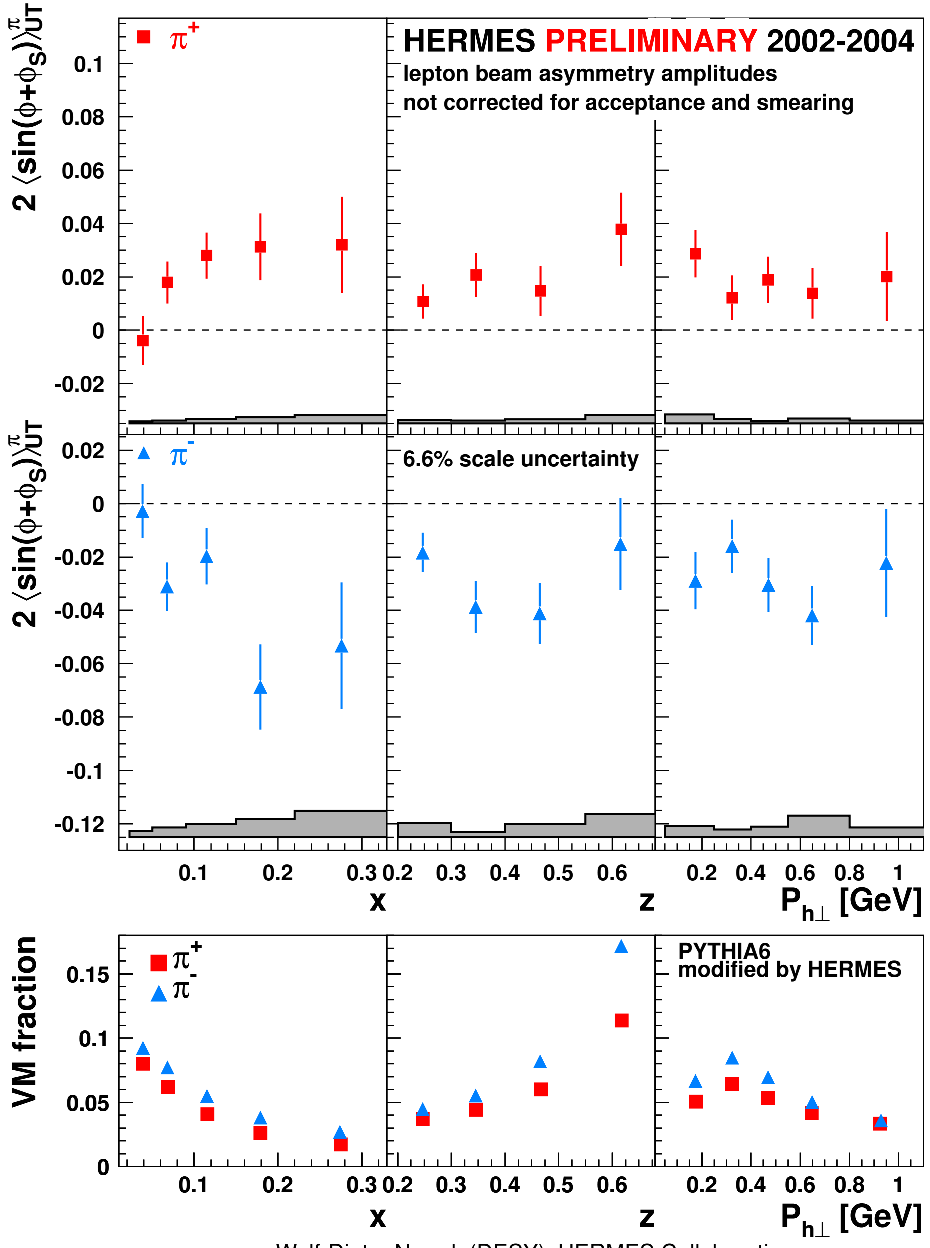
- Exclusive $\rho^0$ asymmetry (2005 prel.):




$\Rightarrow$ small syst. error from vector mesons

# Results on Collins Moments from 2002-2004 data

$$2\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{\ell} \approx 2\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{\gamma^*} \propto \sum_q e_q^2\, \mathcal{I}\left[w_{Coll}\; h_{1T}^q(x,p_T^2)\; H_1^{\perp,q}(z,k_T^2)\right]$$




- positive for $\pi^+$ and negative for $\pi^-$
- agrees with expectation for $\delta q$: positive $\delta u$ and negative $\delta d$
- why large $\pi^-$ asymmetry (at large $x$) ?
  - neither flavor dominates $\pi^-$ prod.
  - $|\delta d| < |\delta u|$

$\Rightarrow$ disfavored Collins function larger and opposite in sign ? (Artru fragm. model)

- little dependence on $z$

NOTE: asymmetry weighting by $P_{h_\perp}/(zM_h)$ makes convolution integral calculable

$\Rightarrow$ kinematic dependence of asymmetry identical for Sivers, similar for Collins

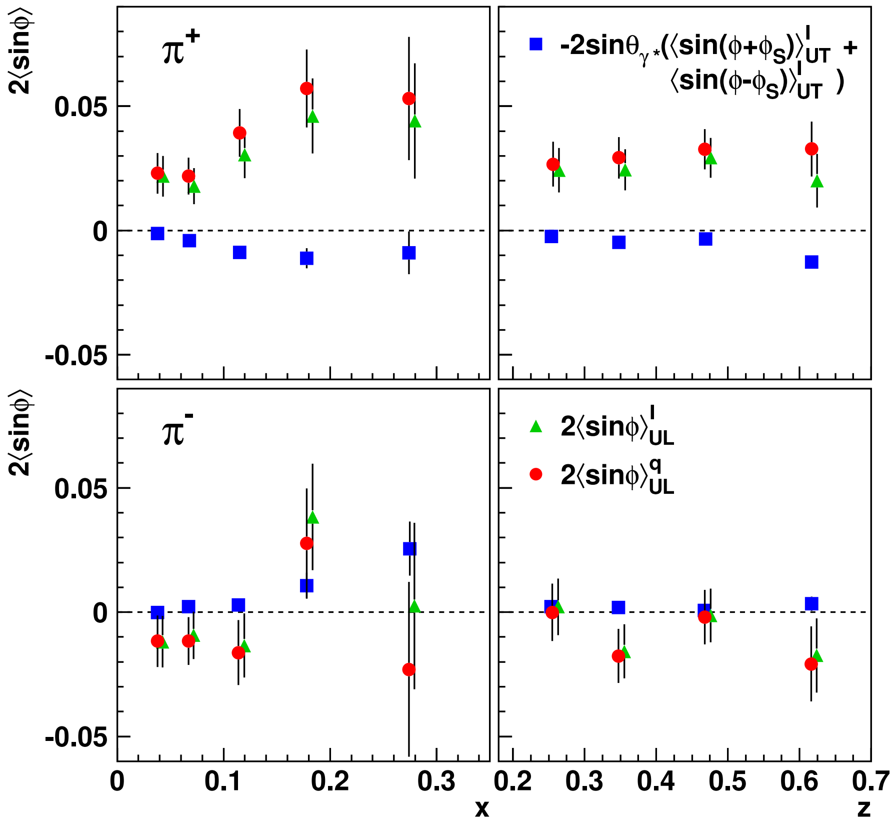
$\Rightarrow$ later: direct extraction of distribution and fragmentation functions possible

# Separation of subleading 1/Q contributions

$$\left\langle \sin\phi \right\rangle_{UL}^{\gamma^*} = \left\langle \sin\phi \right\rangle_{UL}^{\ell} + \sin\theta_{\gamma^*}\left( \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\ell} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\ell} \right)$$

$$\propto \quad \frac{M}{Q}\,\mathcal{I}\Bigg[\frac{\hat{P}_{h\perp}k_T}{M_h}\left(\frac{M_h}{zM}g_1 G^\perp + x h_L H_1^\perp\right) + \frac{\hat{P}_{h\perp}p_T}{M}\left(\frac{M_h}{zM}h_{1L}^\perp \tilde{H} - x f_L^\perp D_1\right)\Bigg]$$

- each term involves either a distribution or a fragmentation function that is subleading in 1/Q




**Thy: Bacchetta et al., Phys. Lett. B595 (2004) 309**

$\mathbf{A}_{UL}$: **Airapetian et al., PRL 84 (2000) 4047**

**Subl.: Airapetian et al., Phys. Lett. B622 (2005) 14**

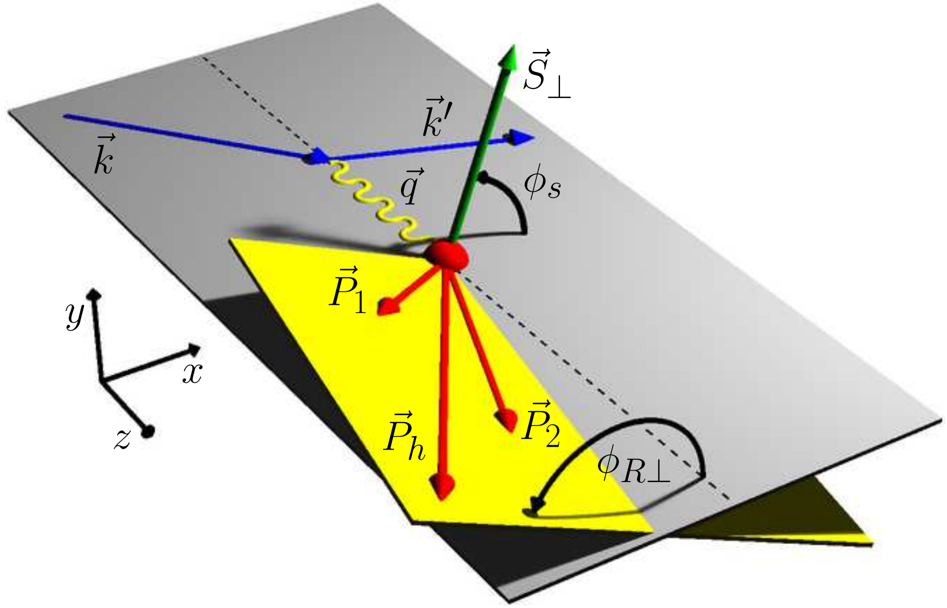
- Subleading twist dominates $\mathbf{A_{UL}}$:

$\Rightarrow$ positive for $\pi^+$; zero for $\pi^-$

# Transversity in 2-pion Fragmentation

Another tool to access transversity, independ. from 1-pion analysis:

- production of 2 pions close to $M_\rho$
- interference of s- and p-waves of 2-pion system
- NO convolution integral
- after integration over $P_{h\perp}$:



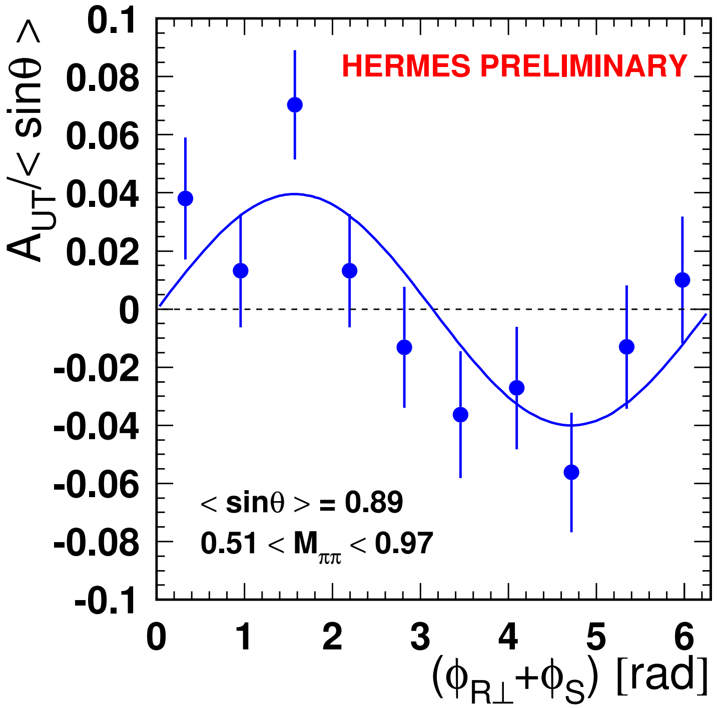

$$\boxed{\sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sum e_q^2 \ \sin\theta \ h_1 \ H_1^{\sphericalangle}}$$

Interference fragmentation function: $H_1^{\sphericalangle} = H_1^{\sphericalangle}(z, \zeta, M_{\pi\pi}^2)$; $\zeta \sim z_1/(z_1 + z_2)$

Two contradicting theory predictions for behaviour in $\rho$ mass range:

- **Jaffe et al.[hep=ph/9709322]:** sign change of $H_1^{\sphericalangle}$
- **Radici et al. [hep-ph/0110252]:** 'resonance shape' of $A_{UT}$

# 2-pion asymmetry on transversely polarized target




$$A_{UT}(\phi_{R\perp},\phi_S,\theta) = \frac{1}{\langle S_T \rangle}\frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}}$$

**fit** $\frac{A_{UT}}{\langle \sin\theta \rangle} = P_1 + P_2 \sin(\phi_{R\perp} + \phi_S)$

$\Rightarrow$ **significant sine modulation:**

$$\boxed{A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} = 0.040 \pm 0.009_{\text{stat}} \pm 0.003_{\text{sys}}}$$

$\Rightarrow$ Interference fragmentation function (IFF) must be non-zero

BUT: $\mathbf{h_1}$ extraction needs IFF measurement from BELLE or BABAR

NOTE: measured mass dependence favors model of Radici et al.

# Summary and Outlook

- The 'Sivers' and 'Collins' moments of the transverse single-spin asymmetry $A_{UT}^{\pi}$ were disentangled by HERMES for the first time
- The $u$-quark T-odd 'Sivers' function appears to have a negative first moment
- From $\pi^+$ and $\pi^-$ 'Collins' moments the fragmentation disfavored in quark flavor appears surprisingly large and with a sign opposite to that of the favored case
- First indication for non-zero interference fragmentation function seen in $A_{UT}^{2\pi}$
- $A_{UL}^{\pi}$ shown to be dominated by subleading twist

**Data taking with transversely polarized hydrogen target continues till end of 2005:**

$\Rightarrow$ Final statistics may allow successful analysis of additional channels to access transversity:

- Spin-1 ($\rho$) and spin-$\frac{1}{2}$ ($\Lambda$) fragmentation
- polarized beam $\Rightarrow A_{LT}$ in pion prod. (measurement of transversity in conjct. with **twist-3 fragmentation function**)